Effect of center of mass and handle location of two-wheeled refuse containers on mechanical loading

Kingma, I.; Kuijer, P.P.F.M.; Hoozemans, M.J.M.; van Dieen, J.H.; van de Beek, A.; Frings-Dresen, M.H.W.

published in
IEA 2000 / HFES 2000 Congress
2000

EFFECT OF CENTER OF MASS AND HANDLE LOCATION OF TWO-WHEELED REFUSE CONTAINERS ON MECHANICAL LOADING

Idsart Kingma[1], P. Paul F.M. Kuijer[1,2], Marco J.M. Hoozemans[2], Jaap H. van Dieën[1], Allard J. van der Beek[3], Monique H.W. Frings-Dresen[2]

[1] Faculty of Human Movement Sciences, Vrije Universiteit, Amsterdam, The Netherlands

[2] Coronel Institute for Occupational and Environmental Health, Academic Medical Center / University of Amsterdam, Amsterdam, The Netherlands

[3] Department of Public Health, Erasmus University Rotterdam, The Netherlands

The aim of the current study was to find out how the center of mass (COM) and handle location of a two-wheeled container affects handle forces and joint loading. Forces at the handles and joint loading were quantified in four subjects during steady, two-handed pushing and pulling of two-wheeled containers with nine different COM locations and eleven different handle locations. The COM location turned out to have a major influence on handle forces and joint loading, whereas the influence of the handle location was moderate. Subjects considerably adapted the tilt angle of the container in response to variations in handle location but hardly in response to variations in COM location. For two-handed pushing and pulling the current design of a two-wheeled container can be improved by moving the centre of mass of the loaded container in the direction of the axis of the wheels and by slightly increasing the height of the handles.

INTRODUCTION

With growing awareness of the risk of lifting activities for developing musculoskeletal disorders (NIOSH 1997), tasks that used to involve frequent lifting are being replaced by pushing and pulling tasks. For instance, in refuse collecting, two-wheeled containers have been recommended to replace bags (Frings-Dresen *et al.* 1995), resulting in a marked reduction of compressive forces at the low back (De Looze *et al.* 1995). However, pushing and pulling is also known to be one of the risk factors for low back injuries and shoulder complaints (Hoozemans *et al.* 1998, Van der Beek *et al.* 1993).

The design of a two-wheeled container affects hand forces and joint loading during pushing and pulling. Two parameters seem of importance : handle height and center of mass (COM). Okunribido and Haslegrave (1999) reported in a study on two-wheeled trolleys, used to transport gas cylinders, that the height and the angle of the handle did affect the tilt angle of the trolley. In turn, this tilt angle affects the position of the handles and of the center of mass (COM) with respect to the axis of the wheels, thereby influencing the required forces at the handle and the resulting joint loading. The location of the COM of a loaded two-wheeled container is another important aspect of the design that might affect mechanical loading of the joints during pushing and pulling. Given a specific tilt angle, a forward or backward shift of the COM immediately affects the required vertical force due to a change of the moment arm of the COM with respect to the axis of the wheels. It should be noted here, that due to the tilting of two-wheeled containers, not only the forward-backward location but also the height of the COM affects joint loading. For instance, Van der Beek et al. (1999) reported a three-fold increase of lumbar compressive forces when the COM height was increased by inserting a tray in a two-wheeled container. The main aim of the current study is to find out how the design of a two-wheeled container, in terms of its COM and handle location, affects handle forces and joint loading during steady, two-handed pushing and pulling.

METHODS

Subjects and materials

Four experienced male refuse collectors participated in the experiment after signing an informed consent. Subject height is the most likely anthropometric parameter to influence posture and joint loading during pushing and pulling of two-wheeled containers. Therefore, refuse collectors with a large range in body height were selected. Subject height and body weight were 1.64 m, 66.6 kg; 1.72 m, 65 kg; 1.85 m, 86 kg; 1.93 m, 80 kg respectively. Two standard Dutch refuse containers (Otto, 0.240 m^3) were used for the experiment (figure 1).

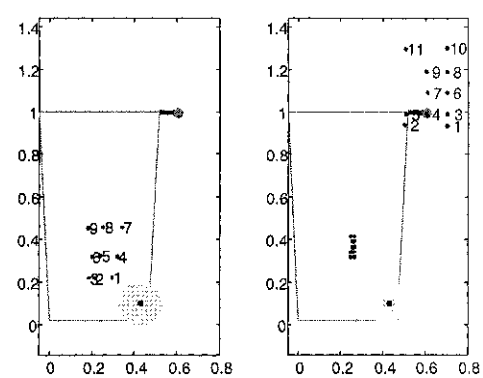

Figure 1. The 9 COM and 11 handle locations

an opto-electronic system (Optotrac). Exerted forces and marker positions were sampled at 50 Hz.

Biomechanical model

Kinematics and anthropometrical data were used as input for an upper body static 3D linked segment model. The biomechanical model consisted of five segments: left and right forearm plus hand, left and right upper arm, and trunk plus head. Relative segment masses and segment center of mass locations were obtained from Plagenhoef *et al.* (1983). Net moments at the L5-S1 level were calculated using standard linked segment mechanics.

Electromyography

During the experimental pushing and pulling activities surface-EMG recordings were made of eight bilateral muscle pairs of the trunk (multifidus, longissimus thoracis, iliocostalis lumborum, rectus abdominis, obliquus externus abdominis, obliquus internus abdominis; Van Dieën 1997) using bipolar disposable Ag-AgCl electrodes. Signals were amplified 20 times, band-pass pre-filtered (10-400 Hz) and A-D converted (22 bits at 1600 Hz). A pulse generator was used to provide a block pulse to synchronize signals from the external forces and kinematics with the EMG-data.

To provide a basis for normalization of EMG data from the experiments, maximum EMG amplitudes of all muscles were determined by seven maximum voluntary contraction (MVC) tests derived from McGill (1991). The MVC tests started with maximal isometric trunk flexion, clockwise trunk twisting and anti-clockwise trunk twisting (all three in a bent-knee sit up posture with a trunk-angle 30° from horizontal). Next, the participants had to perform maximal isometric trunk flexion, trunk extension, and lateral trunk bending to the left and to the right (the last four in a hanging posture in a supine, prone, and lying on the left and right side posture respectively with a trunk-angle 0° from horizontal). Each test was performed twice. The muscle forces exerted by the subject were resisted by gravity and by additional manual forces of the experimenter. During performance the legs were fixed to a bench, and the subjects were instructed to keep their hands behind their heads.

All signals were high-pass filtered (FIR) at 30 Hz to reduce cardio-electric interference (Redfern *et al.* 1993), and subsequently low-pass filtered (Butterworth) at 2.5 Hz after full-wave rectification. Filtered data were normalized to the maximum value found for each muscle in the MVC tests. The processed data were used as input in the EMG-driven model. Afterwards all data was reduced to 10 Hz by using a 10-point running average.

Calculation of compressive forces and shear forces

An EMG driven distribution model was used to estimate compressive and shear forces. The model, containing 90 muscle slips crossing the L5-S1 joint, has in part been described previously (Van Dieën and Kingma 1999). Muscle forces were estimated as the product of maximum muscle stress, normalized EMG amplitude, and correction factors for instantaneous muscle length and contraction velocity plus the passive force developed by the muscle's connective tissue. The correction factors are based on dynamical properties of human and animal muscles as described by Van Zandwijk (1998) and the passive length tension properties were modeled after Woittiez *et al.* (1984). Maximum muscle stress was iteratively adjusted to obtain maximum agreement between the time series of muscle moments and net external moments (cf. McGill and Norman 1986).

Compressive forces were determined by the sum of the tension of all 90 muscle slips in axial direction with regard to the position of the L5-S1 inter-vertebral disc (27.2° inclined from vertical). The mass of the upper body (58.72% of the total body weight (Plagenhoef *et al.* 1983)) was multiplied by gravity and the cosine of the inclination angle of the L5-S1 inter-vertebral disc and added to the compressive forces. Both horizontal and vertical external forces were multiplied by the sine and the cosine of the inclination angle, respectively, and added to the compressive forces as well. Compressive forces are considered positive when the 5th lumbar vertebra moves towards the sacrum.

To determine shear forces, the same procedure was applied in anterior-posterior direction with regard to the position of the L5-S1 inter-vertebral disc. Shear forces are considered positive when the 5th lumbar vertebra moves posterior with regard to the position of the sacrum.

Analyses

The peak net moment, peak compressive force, and peak shear force were determined for each measured condition. Analysis of variance with a repeated measurements design was performed to detect differences among handle heights and among pushing and pulling. A significance level of 5% was used.

RESULTS

Initial analyses of the EMG showed antagonistic co-activity during pushing, which is essential for distribution of the net moment at L5-S1. Figure 1 shows a typical example of the agonistic and antagonistic muscle activity during pushing as well as pulling of a 320 kg cart at hip height. During pulling the agonistic (back) muscles are clearly active, while the antagonistic (abdominal) muscle are relatively inactive. However, during pushing both agonistic and antagonistic muscles are active, which will effect the distribution of the L5-S1 net moment and as a result the compressive and shear forces.

Table 1, 2, and 3 present the results of the analysis of variance. Mean, standard variations and p-values are given for peak net moment, peak compressive force, and peak shear force, respectively.

Pushing and pulling at hip height resulted in significantly increased peak net moments, peak compressive forces, and peak shear forces as compared to pushing and pulling at shoulder height. Peak compressive forces during pushing and pulling at hip height were 4395 N and 5073 N, respectively.

For pushing and pulling at shoulder height peak compressive forces were 2815 N and 3339 N, respectively. The increase in peak compressive forces as a result of the usage of the lower handle height was about 1500 N.

For the peak net moments the differences between pushing and pulling were significant. However, these differences in peak net moments did not result in differences in peak compressive forces (p=0.386). Although pulling resulted in significantly higher peak net moments, the EMG assisted model distributed the net moments such that the differences in peak compressive forces between pushing and pulling were not statistically different. Table 3 shows that pushing or pulling did effect the peak shear forces. Significantly larger peak shear forces were found during pulling.

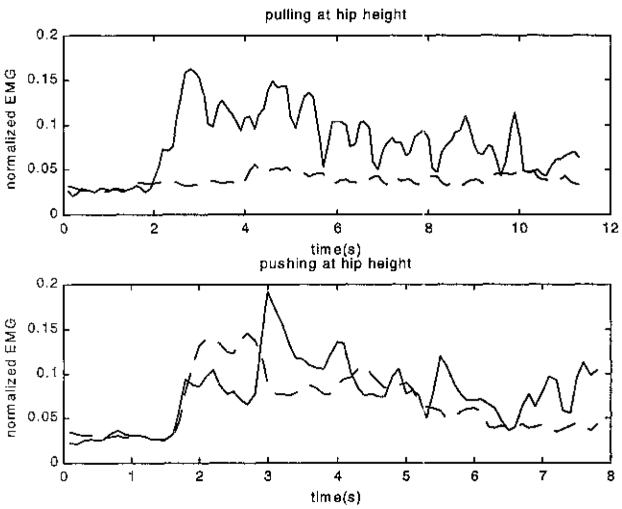

Figure 1: Agonistic (solid line) and antagonistic (dashed line) muscle activity presented as normalized EMG. A typical example is presented of pulling and pushing a 320 kg four-wheeled cart at hip height.

Table 1: Results of peak net moments (Nm) during pushing and pulling at different handle heights.

	pushing		pulling	
	mean	SD	mean	SD
hip	138	25	168	43
shoulder	84	14	150	34
hip vs shoulder	p=0.004			
pushing vs pulling	p=0.012			

Table 2: Results of peak compressive forces (N) during pushing and pulling at different handle heights.

	pushing		pulling	
	mean	SD	mean	SD
hip	4395	786	5073	1802
shoulder	2815	1196	3339	857
hip vs shoulder	p=0.004			
pushing vs pulling	p=0.386			

Table 3: Results of peak shear forces (N) during pushing and pulling at different handle heights.

	pushing		pulling	
	mean	SD	mean	SD
hip	-1364	589	-2149	843
shoulder	-879	670	-1171	302
hip vs shoulder	p=0.001			
pushing vs pulling	p=0.026			

DISCUSSION

The aim of this study was to assess peak net moments, peak compressive and peak shear forces at the L5-S1 level in dynamic pushing and pulling at two different handle heights. Compressive and shear forces were estimated with net moments calculated using a linked segment model combined with an EMG assisted model to distribute the net moment (Van Dieën 1997). The results of the present study suggest that pushing and pulling at shoulder height is associated with significantly lower peak net moments, peak compressive and shear forces on the L5-S1 inter-vertebral disc than pushing and pulling at hip height.

Most striking is that peak compressive forces were not significantly different between pushing and pulling, while the peak net moments were significantly higher during pulling. This result can be largely explained by differences in co-contractions of agonistic and antagonistic muscles between pushing and pulling (figure 1). Antagonistic muscle activity is clearly present during pushing and the activity is considerable. Distribution of the net moment using the EMG model resulted therefore in a relative increase of compressive forces as a result of co-contraction although net moments appeared to be relatively low. These findings demonstrate the necessity of an EMG assisted model to estimate compressive forces, at least for activities were antagonistic co-activity is expected. The use of SEM, which is often used to estimate lumbosacral loads, would have underestimated the compressive forces during pushing. Van Dieën and De Looze (1999) showed that the sensitivity of compression and shear estimates was considerable when co-activity was assumed to be present.

Peak compressive forces found in the present experiments were relatively high. Pushing and pulling at hip height of a 320 kg cart resulted in peak compressive forces of over 4000 N. For the Dutch Postal Services it is expected that the daily frequency of these peak compressive forces is over 500 (unpublished data). The risk for low back complaints could therefore be considerable. However, Van Dieën and De Looze (1999) indicate that the model used in the present study may overestimate the compressive forces. They state that the anatomical data used for the model represent a somewhat smaller than average male. Hence, the lever arms of the muscles in the model are relatively small and relatively larger muscle forces are necessary to account for the actual net moments which will result in relatively larger compressive forces.

The relation between handle height during pushing and pulling and the load on the low back has often been the subject of investigation (Ayoub and McDaniel 1974, Chaffin *et al.* 1983, Lee *et al.* 1991, Gagnon *et al.* 1992, Kumar 1994, Resnick and Chaffin 1995, Van der Woude *et al.* 1995, De Looze *et al.* in press). Generally, these studies reported that higher handle heights reduces mechanical stress on the lower back during pushing and pulling, either in terms of net moments or in terms of compressive and shear forces. This can also be confirmed by the results of the present study.

However, large contrasts are present between these studies, and also in relation to the present study, with respect to the level of the compressive and shear forces reported and with respect to the differences between pushing and pulling. These contrasts can be largely explained by the distribution model that is used. It is clear that the distribution of the net moment is crucial for the interpretation of compressive and shear forces. For pulling, co-activity of antagonistic muscles was low. Because a strong relationship was found between peak net moments and peak compressive forces during lifting and pulling loads, Van Dieen *et al.* (2000) suggest that SEMs could be used to study (symmetric) lifting and pulling tasks. However, in pushing, the presence of co-activity of the back and abdominal muscles makes the use of SEM invalid. Hence, the conclusions of most of the studies reported above are questionable.

With respect to low back loading, the present study could not discriminate between pushing or pulling loads as a favorable action. However, it can be advised to avoid pushing and pulling at low handle heights. Pushing and pulling at shoulder height is to be recommended. For future research concerning biomechanical loading during pushing and pulling it is recommended to pay attention to the mechanical loading of the shoulder joints.

REFERENCES

Ayoub, M.M. and McDaniel, J.W. Effects of operator stance on pushing and pulling tasks. AIIE Transactions 6(3):185-195, 1974.

Andres, R.O. and Chaffin, D.B. Validation of a biodynamic model of pushing and pulling. J.Biomechanics 24(11):1033-1045, 1991.

Baril-Gingras, G. and Lortie, M. The handling of objects other than boxes: univariate analysis of handling techniques in a large transport company. Ergonomics 38(5):905-925, 1995.

Chaffin, D.B., Andres, R.O., and Garg, A. Volitional postures during maximal push/pull exertions in the sagittal plane. Human Factors 25(5):541-550, 1983.

De Looze, M.P., Van Greuningen, K., Rebel, J., Kingma, I., and Kuijer, P.P.F.M. Force direction and physical load in dynamic pushing and pulling. Ergonomics, in press.

Gagnon, M., Beaugrand, S., and Authier, M. The dynamics of pushing loads onto shelves of different heights. Int.J.Ind.Ergon. 9:1-13, 1992..

Hoozemans, M.J.M., Van der Beek, A.J., Frings-Dresen, M.H.W., Van Dijk, F.J.H., and Van der Woude, L.H.V. Pushing and pulling in relation to musculoskeletal disorders: a review of risk factors. Ergonomics 41(6):757-781, 1998.

Kuiper, J.I., Burdorf, A., Verbeek, J.H.A.M., Frings-Dresen, M.H.W., Van der Beek, A.J., and Viikari-Juntura, E. Epidemiological evidence on manual materials handling as a risk factor for back disorders: a systematic review. Int.J.Ind.Ergon. 24:389-404, 1999.

Kumar, S. The back compressive forces during maximal push-pull activities in the sagittal plane. J.Human Ergol. 23(2):133-150, 1994.

Lee, K.S., Chaffin, D.B., Waikar, A., and Chung, M.K. Lower back muscle forces in pushing and pulling. Ergonomics 32(12):1551-1563, 1989.

Lee, K.S., Chaffin, D.B., Herrin, G.D., and Waikar, A. Effect of handle height on lower-back loading in cart pushing and pulling. Appl.Ergon. 22(2):117-123, 1991.

McGill, S.M. Electromyographic activity of the abdominal and low back musculature during the generation of isometric and dynamic axial trunk torque: implications for lumbar mechanics. J.Orthop.Res. 9:91-103, 1991.

McGill, S.M. and Norman, R.W. Partitioning of the L4-L5 dynamic moment into disc ligamentous and muscular components during lifting. Spine 11:666-677, 1986.

Plagenhoef, S., Evans, F.G., and Abdelnour, T. Anatomical data for analyzing human motion. Research Quarterly for Exercise and Sport 54:169-178, 1983.

Redfern, M.S., Hughes, R.E., and Chaffin, D.B. High-pass filtering to remove electrocardiographic interference from torso EMG recordings. Clin.Biomech. 8:44-48, 1993.

Resnick, M.L. and Chaffin, D.B. An ergonomic evaluation of handle height and load in maximal and submaximal cart pushing. Appl.Ergon. 26(3):173-178, 1995.

Van der Woude, L.H.V., Van Koningsbruggen, C.M., Kroes, A.L., and Kingma, I. Effect of push handle height on net moments and forces on the musculoskeletal system during standardized wheelchair pushing tasks. Prosthetics and Orthotics International 19(3):188-201, 1995.

Van Dieën, J.H. Are recruitment patterns of the trunk musculature compatible with a synergy based on the maximization of endurance? J.Biomechanics 30(11/12):1095-1100, 1997.

Van Dieën, J.H. and De Looze, M.P. Sensitivity of single-equivalent trunk extensor muscle models to anatomical and functional assumptions. J.Biomechanics 32:195-198, 1999.

Van Dieën, J.H. and Kingma, I. Total trunk muscle force and spinal compression are lower in asymmetric moments as compared to pure extension moments. J.Biomechanics 32:681-687, 1999.

Van Dieën, J.H., Hoozemans, M.J.M., Van der Burg, P., Jansen, J.P., Kingma, I., and Kuijer, P.P.F.M. The importance of antagonistic co-contraction of trunk muscles for spinal loads during lifting and pulling tasks: implications for modeling approaches. International Ergonomics Association: 14th triennial congress San Diego US, 2000.

Van Zandwijk, J.P. The dynamics of muscle force development. An experimental and simulation study of the behavior of human skeletal muscles. Thesis Vrije Universiteit Amsterdam, 1998.

Woittiez, R.D., Huijing, P.A., Boom, H.K.B., and Rozendal, R.H. A three-dimensional muscle model: a quantified relation between form and function of skeletal muscles. Journal of Morphology 182:95-113, 1984.